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13. ABSTRACT *(Maximum 200 words)*

The main objective of this grant was to conduct a careful and exhaustive experimental examination of the charging effect in high-temperature superconducting (HTS) thin films and perform research on novel superconducting electronic and optoelectronic devices operational at liquid-nitrogen temperatures. For this purpose, we developed a new, laser-based approach to processing of YBa2Cu3Ox (YBCO) thin films, exploiting the contrasting optical and electrical properties of the oxygen-poor (semiconducting) and oxygen-rich (superconducting) YBCO phases. Using laser writing, we fabricated, superconducting SuperFET structures, which consisted of a channel based on partially oxygen-depleted material or a Josephson weak-link, and fully superconducting source and drain electrodes. We also developed microwave transmission lines, structures with nonuniform oxygen doping profiles, and photodetectors based on YBCO films containing regions with different oxygen contents. The physical mechanisms behind the performance of our test structures were investigated with the emphasis on their electrical and optoelectronic properties. Our interest was extended to studies of laser induced modifications of YBCO Josephson junctions and photoinduced oxygen reordering within grain-boundary weak links. Our basic physics experiments were aimed to investigate superconducting transport and superconducting fluctuations in HTS materials, especially in case of partially oxygen-depleted materials, when carriers were optically created.

14. SUBJECT TERMS

superconducting electronics, high-temperature, superconductivity, the charging effect, laser-writing technique of superconducting three-terminal devices, optical properties of superconductors and bolometers

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The Charging Effect in High-T_c Superconducting Thin Films

FINAL PROGRESS REPORT
January 1, 1994 - June 30, 1997

AIR FORCE OFFICE FOR SCIENTIFIC RESEARCH
F49620-94-1-0094

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DEPARTMENT OF ELECTRICAL ENGINEERING
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RESEARCH FINDINGS

I. Specific Aims and Research Objectives

The main objective of this grant was to conduct a careful and exhaustive experimental examination of the charging effect in high-temperature superconducting (HTS) thin films and perform research on novel superconducting devices operational at liquid-nitrogen temperatures. For this purpose, we developed a new, laser-based approach to processing of $YBa_2Cu_3O_x$ (YBCO) thin films, exploiting the contrasting optical and electrical properties of the oxygen-poor (semiconducting) and oxygen-rich (superconducting) YBCO phases. Using laser writing, we fabricated, superconducting SuperFET structures, which consisted of a channel based on partially oxygen-depleted material or a Josephson weak-link, and fully superconducting source and drain electrodes. We also developed microwave transmission lines, structures with nonuniform oxygen doping profiles, and photodetectors based on YBCO films containing regions with different oxygen contents. The physical mechanisms behind the performance of our test structures were investigated with the emphasis on their electrical and optoelectronic properties. Our interest was extended to studies of laser-induced modifications of YBCO Josephson junctions and photoinduced oxygen reordering within grain-boundary weak links. Our basic physics experiments were aimed to investigate superconducting transport and superconducting fluctuations in HTS materials, especially in case of partially oxygen-depleted materials, when carriers were optically created.

II. Research Accomplishments and Results

II.A. Laser-processing technique

We have developed a laser-processing technique, suitable for fabrication of monolithic YBCO devices. The method is based on the observation that YBCO electrical and optical properties are very sensitive to the material's oxygen content. In particular, we designed a method for patterning of both plain YBCO films and *in-situ* grown YBCO/$SrTiO_3$ bilayers. The patterning is achieved through both laser inhibition, in which an intense, focused laser beam locally melts YBCO transferring it into an insulating glass-like material, and laser writing, based on a laser-controlled diffusion of oxygen in or out of the YBCO film. Using laser inhibition and writing, we were able to fabricate a variety of YBCO devices, showing that laser processing can be successfully used in patterning and/or electrical trimming of multilayered YBCO circuits. Several new analytical techniques, such Raman spectroscopy, optical and scanning electron microscopy, and electrical tunneling and transport measurements were implemented to characterize our laser-processed structures.

The laser-processing technique is noninvasive, does not require a patterning mask, and results in completely planar structures free of surface contamination. We fabricated laser-patterned HTS structures for the collaborative research with the following research institutions: NIST, Boulder, CO, SMU, Dallas, TX, UofHouston, Houston, TX, Imperial College, London, England, Boltzmann Institute, Vienna, Austria, Institute of Physics, Warsaw, Poland, Hebrew University, Jerusalem, Israel, Ben-Gurion University, Beer-Sheva, Israel.

Invention disclosure was submitted on our laser-processing technique. However, the Research Corporation Technologies (UofR patent collaborator) postponed its action due to the fact that (quote) "currently, the market for such a method is limited, making licensing this technology difficult."

II.B. SuperFET design and testing

A number of charging-effect SuperFETs have been fabricated. The structures were fully monolithic and consisted of a partially oxygen depleted channel (T_c = 10÷60 K, depending on the design) and oxygen-rich, fully superconducting ($T_c \approx 90$ K) source and drain electrodes. The fabrication process was based on the laser-writing technique. Our experimental results lead us to a conclusion that the field effect observed in our samples is related to the field-enhanced modification of the channel's crystalline structure, rather than to the simple electrostatic response of mobile holes. The observed behavior was pleasurably explained using the oxygen-reordering model proposed by Chandrasekhar *et al.* Transistor-like structures were also formed on bicrystal substrates *in-situ* covered with a $SrTiO_3$ cap layer and defined via laser processing with the gate electrode evaporated on $SrTiO_3$. Our main result coming from this research, showing that the YBCO SuperFET is intrinsically a slow device, was a major disappointment from the point of view of applications. It is now widely accepted that YBCO-based FET-like structures are not promising as new breed of high-performance electronic devices.

The above research was done in a very close collaboration with the Northrop-Grumman S&T Center, Pittsburgh, PA.

II.C. Laser annealing of YBCO step-edge junctions

The 2- to 20-µm-wide step-edge YBCO junctions from TRW were *in-situ* annealed by illuminating at 50 K with a focused Ar-ion laser beam of the intensity up to 10^6 W/cm.^{2} We observed up to 75% increase of the junction critical current I_c and up to 50% increase of the I_cR_n product, without a measurable change in the junction T_c nor the shape of its RSJ-like current-voltage characteristics. The laser-annealing process leads to the more uniform, higher quality junction barrier, which is due to the increased oxidization of the grain-boundary region. The annealed junctions are stable and remain unchanged even after extensive room temperature/liquid helium thermal cycling.

Our method can be easily extended to complex YBCO chips and is expected to work for circuits containing tens of Josephson junctions. This direction of research is a subject of technology transfer to TRW, aimed at fine adjustment of Josephson junction parameters in digital YBCO circuits.

II.D. Controlled oxygen depth profile for YBCO hybrid superconducting-semiconducting device applications

We have fabricated YBCO thin-film devices with a nonuniform oxygen concentration crossection profile. The structures exhibit a nonuniform oxygen content across the film thickness. The surface-deoxygenated samples find applications for insulating selected parts of YBCO structures from the top and creating planar vias, as well as they can form a basis for Schottky-like structures at the metal-semiconducting-YBCO interface.

The above technology was transferred to the SUPECONIX Inc., St. Paul, MI and was the subject of SUPECONIX SBIR proposal (unfunded— SUPECONIX collapsed).

II.E. Development of Y-Ba-Cu-O microwave circuits with very high-power handling capabilities

We used our laser-writing patterning technique to fabricate high quality coplanar strip (CPS) transmission line devices in epitaxial YBCO thin films deposited on $LaAlO_3$ substrates. In this manner, superconductive CPS surrounded by the semiconducting YBCO phase were patterned with no photomasks, surface contamination, or edge degradation. Our work has demonstrated that the laser-writing technique shows promise for patterning high quality YBCO superconducting thin-film circuits for a variety of microwave applications.

The structures were initially tested at SMU, Dallas, TX. Later this technology was transferred to NIST and adopted by them as one of the three methods for patterning high-power YBCO microwave devices and circuits.

II.F. Superconducting transport and photodoping measurements in HTS thin films and Josephson junctions

Our laser-processing technique was also used to pattern 110-K phase BSCCO films and partially oxygen-depleted ($T_c \approx 60$ K) YBCO samples for studies on normal-state magnetotransport properties and superconducting fluctuations. Measurements of the electrical resistivity, the magnetoresistance, and the Hall effect were analyzed with regard to contributions of the superconducting order-parameter thermodynamic fluctuations, using theories for two-dimensional, layered superconductors. We have found a consisted set of transport parameters for BSCCO, such as in-plane and out-of-plane coherence length and the electron-hole asymmetry. The rapid suppression of the Maki-Thompson process for the oxygen-deficient YBCO films, indicated an unconventional symmetry of the superconducting order parameter.

Comprehensive studies were performed on the photodoping effect in YBCO step-edge Josephson junctions and oxygen-deficient films. We demonstrated that the effect is due to the coexistence of both the photoassisted oxygen ordering, and the light-induced charge transfer processes. The former is mainly responsible for changes of the mobility, while the latter increases carrier concentration. We have also shown that the T_c enhancement and the I_c increase in Josephson junctions are due to photogenerated increase of the carrier concentration rather than change in mobility.

The above research was done in a very close collaboration with the Ludwig Boltzmann Institute for Solid State Physics, Vienna, Austria.

II.G. YBCO bolometric photodetectors

We studied oxygen-poor tetragonal and amorphous YBCO thin-film samples for applications as sensitive photodetectors for infrared detection. The bolometer figures of merit—responsivity and detectivity—were calculated from the measured temperature coefficient of resistance (TCR) and the inherent noise characteristics. The highest TCR of above 4% 1/K was observed in amorphous YBCO films deposited on Si with an MgO buffer layer, while tetragonal films remained in the 2% 1/K range. From TCR and noise measurements, we estimated that the optimized semiconducting YBCO bolometers should have a responsivity as high as 3.8×10^5 V/W and a detectivity as high as 1.6×10^6 cmHz$^{1/2}$/W for 1 μA bias current and standard 30 Hz frame frequency. The above values

are up to two orders of magnitude higher than that reported for superconducting bolometers.

The above research was done in a very close collaboration with the SMU, Dallas, TX.

III. Impact on Applications of Superconductivity

Optoelectronics emerges as one of the most important engineering disciplines of the XXI century. In this context, the development of superconducting optoelectronics becomes also crucial, since it offers (similarly to superconducting electronics) the lowest value of the switching-time–power-consumption product. As we have shown, YBCO material has an number of very interesting and applicable for optoelectronics, optically-induced effects. Simple YBCO photodetectors exhibit single-picosecond response times, making them not only one of the fastest, but, clearly, the cheapest optoelectronic switches. The operating temperature range of YBCO devices enables the full integration with both the superconducting and the conventional (cooled) semiconductor electronics.

IV. Professional Personnel Under Research Grant

Roman Sobolewski (PI)
During the grant period, Dr. Sobolewski was promoted from the rank of Scientist and Adjunct Associate Professor of Electrical Engineering to the Senior Scientist and Professor of Electrical Engineering and Senior Scientist of Laser Energetics.

Witold Kula (post-doc)
Dr. Kula completed his post-doctoral training and left university for a permanent staff position to the CVC Products Inc., Rochester, NY.

Wei Xiong (grad. student)
Dr. Xiong graduated (Ph.D. and M.S. degrees) with honors in 1995 and left for a permanent staff position to the Materials Research Corporation (SONY subsidiary), Orangeburg, NY.
As a graduate student, Xiong was supported by the Frank Horton Laboratory for Laser Energetics Fellowship Program.

Roman Adam (grad. student)
Mr. Adam came to the group as a U.S. Government Fullbright Scholar and now is supported by the Link Foundation Fellowship Program.

Di Wu (grad. student)
Mr. Wu received M.S. degree in Electrical Engineering through a non-thesis M.S. program.

Tamara Kroll (grad. student)
Ms. Kroll received M.S. degree in Electrical Engineering through a non-thesis M.S. program.

V. Thesis and Publications

Ph.D. THESIS (1995)
Wei Xiong, "Fabrication and Optoelectronic Properties of Y-Ba-Cu-O Thin Films with Different Oxygen Contents," Department of Electrical Engineering, University of Rochester, Rochester, NY 14627.

M.S. THESIS (1997)
Roman Adam, "Optically Induced Effects in Y-Ba-Cu-O Josephson Junctions," Department of Electrical Engineering, University of Rochester, Rochester, NY 14627.

The following publications with the grant acknowledgment appeared in print or are currently submitted for publication:

1. "Effect of Hydrogen Doping on Electrical Properties of Y-Ba-Cu-O Thin Films," W. Kula and R. Sobolewski, Physica C 235-240, 587-588 (1994).
2. "Propagation Characteristics of Monolithic Y-Ba-Cu-O Coplanar Strip Transmission Lines Fabricated by Laser-Writing Patterning Technique," W. N. Maung, D. P. Butler, W. Xiong, W. Kula, and R. Sobolewski, IEEE Microwave and Guided Wave Lett. MGWL-4, 132-134 (1994).
3. "Monolithic Y-Ba-Cu-O Structures Fabricated Using the Laser-Writing Patterning Technique," R. Sobolewski, W. Xiong, W. Kula, W. N. Maung, and D. P. Butler, Supercon. Sci. Technol. 7, 300-303 (1994).
4. "Laser Writing: A New Technique for Fabrication of Electronic and Optoelectronic Y-Ba-Cu-O Devices and Circuits," W. Xiong, W. Kula, R. Sobolewski, and J. R. Gavaler, in: Superconductive Devices and Circuits, edited by R. A. Buhrman, J. Clarke, K. Daly, R. H. Koch, J. A. Luine, and R. W. Simon, Proc. SPIE, vol. 2160, pp. 16-24 (1994).
5. "Electric-Field-Effect Devices Based on Partially Oxygen Depleted Superconducting Y-Ba-Cu-O Thin Films," W. Kula and R. Sobolewski, in: Advances in Cryogenic Engineering Materials, edited by R. P. Reed, F. R. Fickett, L. T. Summers, and M. Stieg, vol. 40, part A, pp.377-383 (Plenum Press, New York, 1994).
6. "Fabrication of High Superconducting Electronic Devices Using the Laser-Writing Patterning Technique," W. Xiong, W. Kula, and R. Sobolewski, in: Advances in Cryogenic Engineering Materials, edited by R. P. Reed, F. R. Fickett, L. T. Summers, and M. Stieg, vol. 40, part A, pp.385-391 (Plenum Press, New York, 1994).
7. "Electric-Field Effect in Partially Deoxygenated YBCO Thin Films," W. Kula and R. Sobolewski, Physica B 194-196, 2083-2084 (1994).
8. "Electrical and Structural Properties of the YBCO Superconducting-Semiconducting Interface," R. Sobolewski, W. Xiong, W. Kula, and B. McIntyre, Physica B 194-196, 2143-2144 (1994).
9. "Charging Effect in Partially Oxygen-Depleted Y-Ba-Cu-O Thin Films," W. Kula and R. Sobolewski, Phys. Rev. B Rapid Commun. 49, 6428-6431 (1994).
10. "Laser Patterning of Y-Ba-Cu-O Thin-Film Devices and Circuits," R. Sobolewski, W. Xiong, W. Kula, and J. R. Gavaler, Appl. Phys. Lett. 64, 643-645 (1994).
11. "Microwave Properties of Monolithic Y-Ba-Cu-O Transmission Line Devices Fabricated by the Laser-Writing Patterning Technique," D. P. Butler, W. N. Maung, W. Xiong, W. Kula, and R. Sobolewski, in: High-T_c Microwave Superconductors and Applications, edited by R. B. Hammond and R. S. Withers, Proc. SPIE, vol. 2156, pp. 174-180 (1994).
12. "Y-Ba-Cu-O Thin-Film Structures with a Nonuniform In-Depth Oxygen Concentration Profile," W. Kula, R. Adam, and R. Sobolewski, in: Applied Superconductivity 1995, Institute of Physics Conference Series Number 148,

edited by D. Dew-Hughes, Institute of Physics Publishing (Bristol, 1995), pp. 895-898.

13. "Laser Modification of Transport Properties of Y-Ba-Cu-O Step-Edge Weak Links," R. Adam, W. Kula, R. Sobolewski, J. M. Murduck, and C. Pettiette-Hall, Appl. Phys. Lett. 67, 3801-3803 (1995).
14. "Laser Patterning of $YBa_2Cu_3O_x$ Thin Films Protected by In-Situ Grown $SrTiO_3$ Cap Layers," W. Kula, W. Xiong, R. Sobolewski, and J. Talvacchio, IEEE Trans. Appl. Supercon. 5, 1177 (1995).
16. "Study of Superconducting Fluctuations in $Bi_2Sr_2Ca_2Cu_3O_x$ Thin Films: Paraconductivity, Excess Hall Effect, and Magnetoconductivity," W. Lang, G. Heine, W. Kula, and R. Sobolewski, Phys. Rev. B 51, 9180 (1995).
17. "Laser-Induced Modification of the Critical Current in Y-Ba-Cu-O Step-Edge Josephson Junctions," R. Adam, W. Kula, J. M. Murduck, C. Pettiette-Hall, and R. Sobolewski, Czech. J. Phys. 46, 1321-1322 (1996).
18. "Raman Studies of Laser-Written Patterns in $YBa_2Cu_3O_x$ Films," Y. B. Li, C. Shelley, L. F. Cohen, A. D. Caplin, R. A. Stradling, W. Kula, R. Sobolewski, and J. L. MacManus-Driscoll, J. Appl. Phys. 80, 2929-2935 (1996).
19. "Charge Transport in Amorphous and Tetragonal Semiconducting YBaCuO Films," Z. Celik-Butler, P. C. Shan, D. P. Butler, A. Jahanzeb, C. M. Travers, W. Kula, and R. Sobolewski, Solid St. Electron. 41, 895-899 (1997).
20. "Photodoping Effect in Y-Ba-Cu-O Josephson Junctions and Thin Films," R. Sobolewski, R. Adam, W. Kula, W. Markowitsch, C. Stockinger, W. Göb, and W. Lang, IEEE Trans. Appl. Supercon. 7, 1632-1635 (1997).
21. "Laser Trimming of Y-Ba-Cu-O Step-Edge Josephson Junctions," R. Adam, W. Kula, R. Sobolewski, J. M. Murduck, and C. Pettiette-Hall, IEEE Trans. Appl. Supercon. 7, 2997-3000 (1997).
22. "Hall Effect in Semiconducting Epitaxial and Amorphous Y-Ba-Cu-O Thin Films," P. C. Shan, A. Jahanzeb, D. P. Butler, Z. Celik-Butler, W. Kula, and R. Sobolewski, J. Appl. Phys. 81, 6866-6873 (1997).
23. "Fluctuation-Induced Anisotropic Magnetoconductivity in Oxygen-Deficient $YBa_2Cu_3O_{7-x}$ Thin Films," W. Göb, W. Lang, W. Kula, and R. Sobolewski, Superlatt. and Microstruct. 21, 345-348 (1997).
24. "Optically-Induced Effects in Y-Ba-Cu-O Josephson Junctions, " R. Adam, R. Sobolewski, W. Markowitsch, C. Stockinger, and W. Lang, to appear in Appl. Supercon. (1997).
25. "Contributions to photodoping in Oxygen-Deficient $YBa_2Cu_3O_x$ Films Studied by *in-situ* Transport Measurements," C. Stockinger, W. Markowitsch, W. Lang, W. Kula, and R. Sobolewski, to appear in Z. Phys. B (1997).
26. "Physical and Geometrical Origins of the Normal-State Magnetoresistance in $YBa_2Cu_3O_7$," W. Göb, W. Lang, and R. Sobolewski, to appear in Physica C (1997).
27. "Magnetoresistance of a $YBa_2Cu_3O_7$ Disk: Probing Geometrical Contributions to the Unconventional Normal-State Magnetoresistance of High-Temperature Superconductors," W. Göb, W. Lang, and R. Sobolewski, to appear in Phys. Rev. B - Rapid Commun. (1998).

VI. Conferences and Major Seminars

Invited conference presentations:

1. "Progress in Ultrafast Superconducting Electronics," R. Sobolewski, presented at the International Workshop on Superconductivity and Particle Detection, Toledo, Spain, 1994.
2. "Future Prospects for High Temperature Superconducting Electronics and Optoelectronics," R. Sobolewski, presented at the Austrian Workshop on High Temperature Superconductors, Obertauern, Austria, 1994.
3. "Study of Superconducting Fluctuations in the High-Temperature Superconductors YBCO and BSCCO by Magneto-Transport Measurements," W. Lang, C. Sekirnjak, G. Heine, P. Schwab, S. Proyer, D. Bauerle, W. Kula, and R. Sobolewski, presented at the International Conference of Science and Technology of Synthetic Metals, ICSM'94, Seoul, Korea, 1994.
4. "Ultrafast Characterization of Superconducting Materials and Devices," R. Sobolewski, presented at the 9th International Symposium on Ultrafast Phenomena in Semiconductors, UFPS'95, Vilnius, Lithuania, 1995.
5. "In-situ Resistivity and Hall Effect Studies of Persistent Photoconductivity in Oxygen-Depleted $YBa_2Cu_3O_x$," W. Markowitsch, C. Stockinger, W. Lang, W. Kula, and R. Sobolewski, presented at the Photonics WEST, SPIE International Symposium on Integrated Optoelectronics (OE/LASE'96) - Spectroscopic Studies of Superconductors, San Jose, CA, Jan. 1996.

Contributed communications were presented at 15 international and 9 local (Western New York) conferences.

Major seminars and lectures:

1. "Laser Writing: A New Technique for Fabrication of Electronic and Optoelectronic Y-Ba-Cu-O Devices and Circuits," presented at the Westinghouse Science and Technology Center, Pittsburgh, PA, January 1994.
2. "The Charging Effect in High T_c Superconducting Thin Films," presented during the 3rd STAG/AFOSR Superconductivity Contractors Meeting, Stanford University, Stanford, CA, April 1994.
3. "Electrical and Optical Properties of Superconducting Y-Ba-Cu-O Thin Films," presented at the Department of Physics, University of Salamanca, Salamanca, Spain, April 1994.
4. "The Charging Effect in High T_c Superconducting Thin Films," presented during the 4th STAG/AFOSR Superconductivity Contractors Meeting, Greenbelt, MD, April 1995.
5. "Low Temperature Digital Superconducting Electronics," presented during the 4th STAG/AFOSR Superconductivity Contractors Meeting, Greenbelt, MD, April 1995.
6. "The Charging Effect in High T_c Superconducting Thin Films," presented during the 5th STAG/AFOSR Superconductivity Contractors Meeting, Pittsburgh, PA, March 1996.
7. "Low Temperature Digital Superconducting Electronics," presented during the 5th STAG/AFOSR Superconductivity Contractors Meeting, Pittsburgh, PA, March 1996.
8. "Ultrafast Superconducting Electronics," presented at the Laboratory for Laser Energetics, University of Rochester, Rochester, NY, February 1996.

9. "Optically Induced Phenomena in High-Temperature Superconductors, " presented at the Institute of Physics, Polish Academy of Sciences, Warsaw, Poland, June 1997.

VII. Interactions

We pursued active research interactions and collaborations with the following institutions:

1. Northrop Grumman Science & Technology Center, Pittsburgh, PA.
2. TRW Space and Technology Group, Rodendo Beach, CA.
3. NIST, Boulder, CO.
4. SUPERCONIX, Inc., St. Paul, MI.
5. Texas Center for Superconductivity, Houston, TX.
6. Wright Laboratory, WPAFB, OH.
7. Boltzmann Institute for Solid State Physics, Vienna, Austria.
8. Centre for High-T_c Superconductivity at the Imperial College, London, UK.
9. Southern Methodist University, Dallas, TX.
10. Institute of Physics, Polish Academy of Sciences, Warsaw, Poland.
11. Hebrew University, Jerusalem, Israel.
12. Ben-Gurion University, Beer-Sheva, Israel.

VIII. Honors, professional activities, and awards

1. "The Meritorious Paper Award" at the International Cryogenic Materials Conference, 1993.
2. Dr. Sobolewski was the member of the International Advisory Committee of the 9th International Symposium on Ultrafast Phenomena in Solids, Vilnius, Lithuania, 1995. He was also voted the Member of the International Advisory Committee of the 1998 Symposium.
3. Dr. Sobolewski is an expert for the United Nations Development Programme (UMBRELLA Project -*Advisory Assistance to Poland*).
4. Dr. Sobolewski is a reviewer for the National Science Foundation, the International Science Foundation, and the Air Force Office for Scientific Research and the referee for the Phys. Rev. Lett., Phys. Rev. B, Appl. Phys. Lett., J. Appl. Phys., IEEE Trans. Electron. Devices., and IEEE Trans. Appl. Supercon.
5. Dr. Sobolewski is a "Mentor" for the Ronald E. McNair Post-Baccalaureate Achievement Program.
6. Dr. Sobolewski is the Vice-Chair of the Rochester Chapter of IEEE Electron Device Society.